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Simulation of Silicon Carbide Diode Heating and Natural Convection

by Gregory K. Ovrebo

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Simulation of Silicon Carbide Diode Heating and Natural Convection

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14. ABSTRACT

I modeled two different electronic modules with SiC diodes to be used in pulsed power applications. Cooling in this high power application is provided by natural convection in a bath of oil. SolidWorks was used to construct a computer model and Cosmos FloWorks was used to simulate heating and natural convection in the oil. I applied two 80 W pulses to the modules and calculated temperature increases of approximately 60 °C or less. I also simulated modules heated with a periodic signal over a 60 second period. Results were inconsistent with expectations, casting doubt on the merit of this simulation approach with Cosmos FloWorks.

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1. Introduction

The Army intends to use high power, high temperature silicon carbide (SiC) devices now under development in a number of applications, including power conversion and electric motors. The devices considered here are SiC diodes in series, which would carry wide, high power pulses in quick succession. I used computer simulation to investigate heating of these diode pairs while immersed in oil. Because there is no flow of oil, this is a problem in natural convection. Two different circuit layouts are simulated, with different levels of heating power per diode. I also considered the problem of simulating periodic power waveforms which heat devices over extended periods.

2. Device Models and Simulation Setup

Solid models of the SiC devices were prepared with SolidWorks modeling software. SiC chips 6mm square were placed on aluminum nitride (AlN) substrates. Kovar tabs were placed on top of the SiC chips for electrical contact. The diode assembly was modeled inside an aluminum box which contained one quart of BP oil. The box was a cube roughly 100 mm on a side with walls 2.5 mm thick. Figure 1 shows a layout with 4 diodes, two pairs in parallel. In figure 2, we show a layout with a single diode pair.

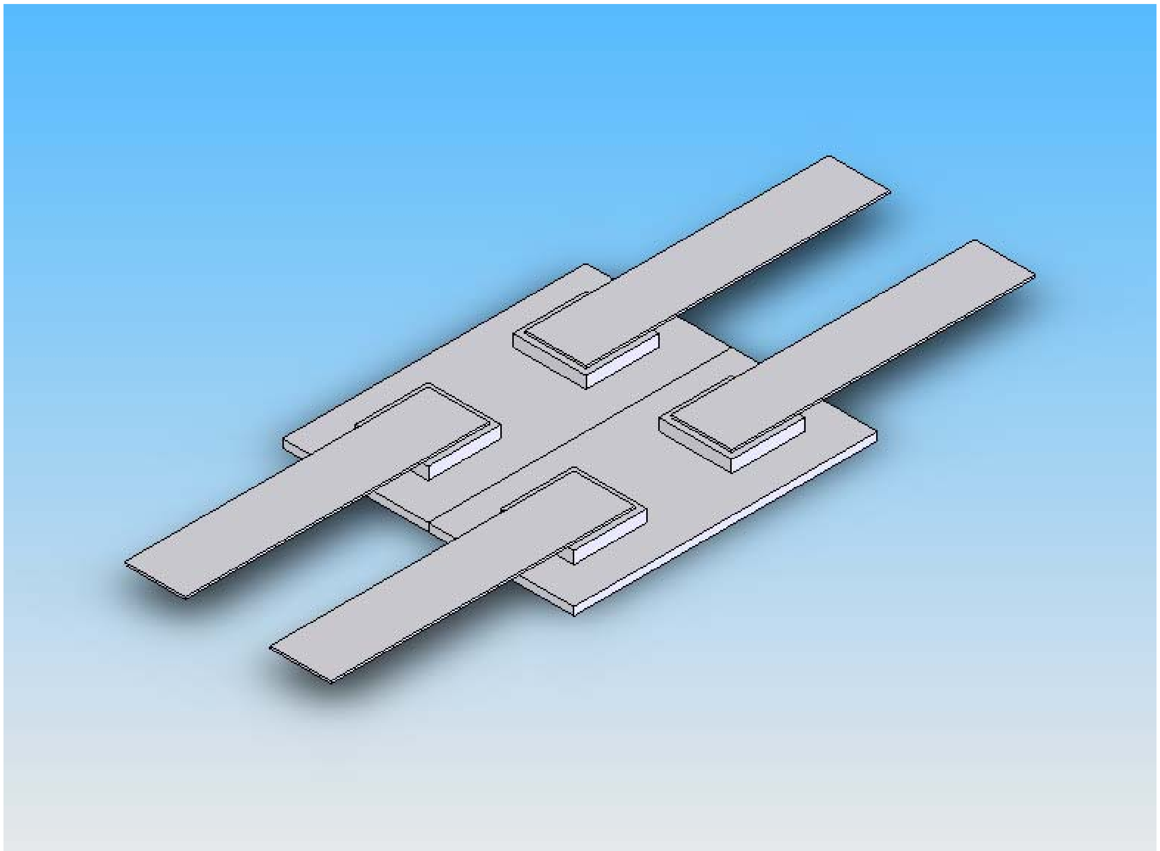

Figure 1. The diode assembly with 4 diodes.

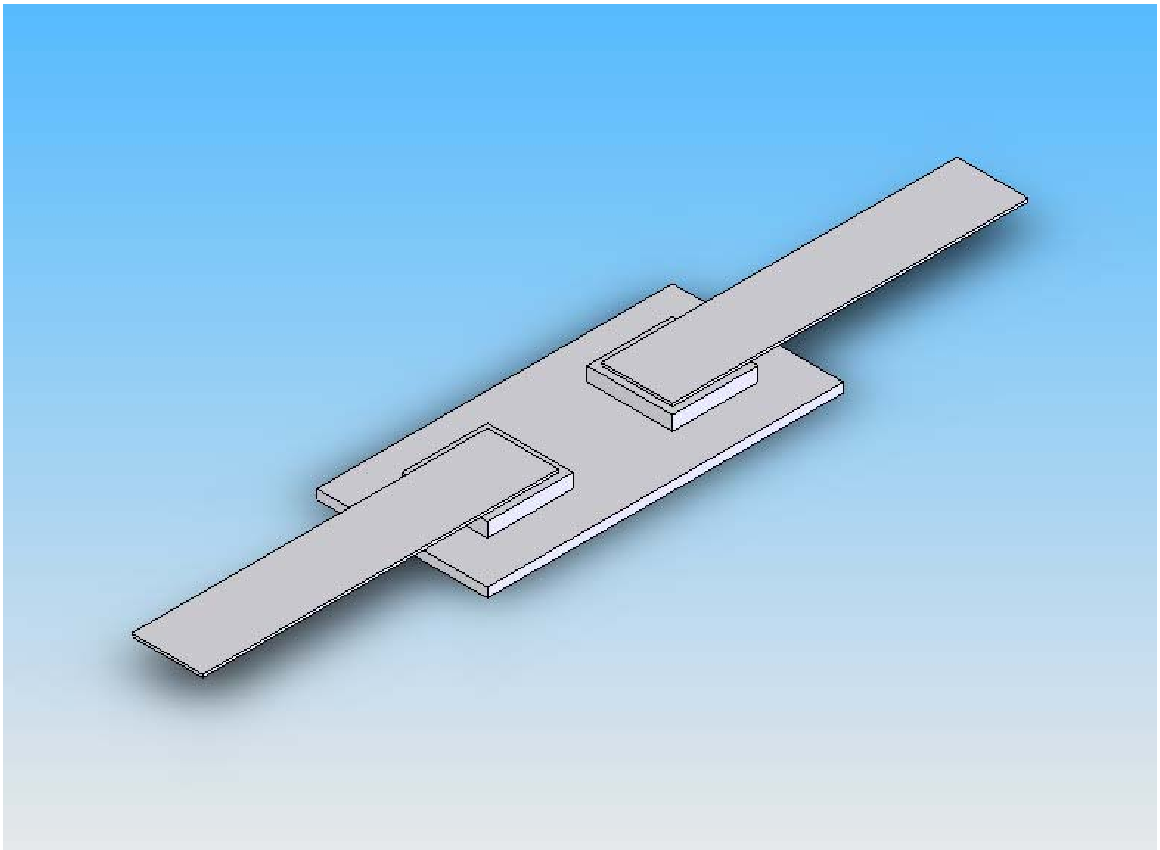

Figure 2. The diode assembly with 2 diodes.

Simulation of the heating and convection in the model was performed with Cosmos FloWorks, a computational fluid dynamics code which can perform finite element calculations of fluid flow and heat transfer on SolidWorks models. I specified materials for each part of the model, as well as heat sources, heat sinks, and other boundary conditions. The physical properties of the aluminum, Kovar, AlN, and SiC were entered into the Floworks model, along with the properties of the oil. The oil's physical properties were defined with values for specific heat, density, and viscosity which varied with temperature. Figure 3 shows a diode assembly in the center of the aluminum box, as it was modeled in the thermal simulation. The space inside the box surrounding the diode assembly is defined to be BP oil.

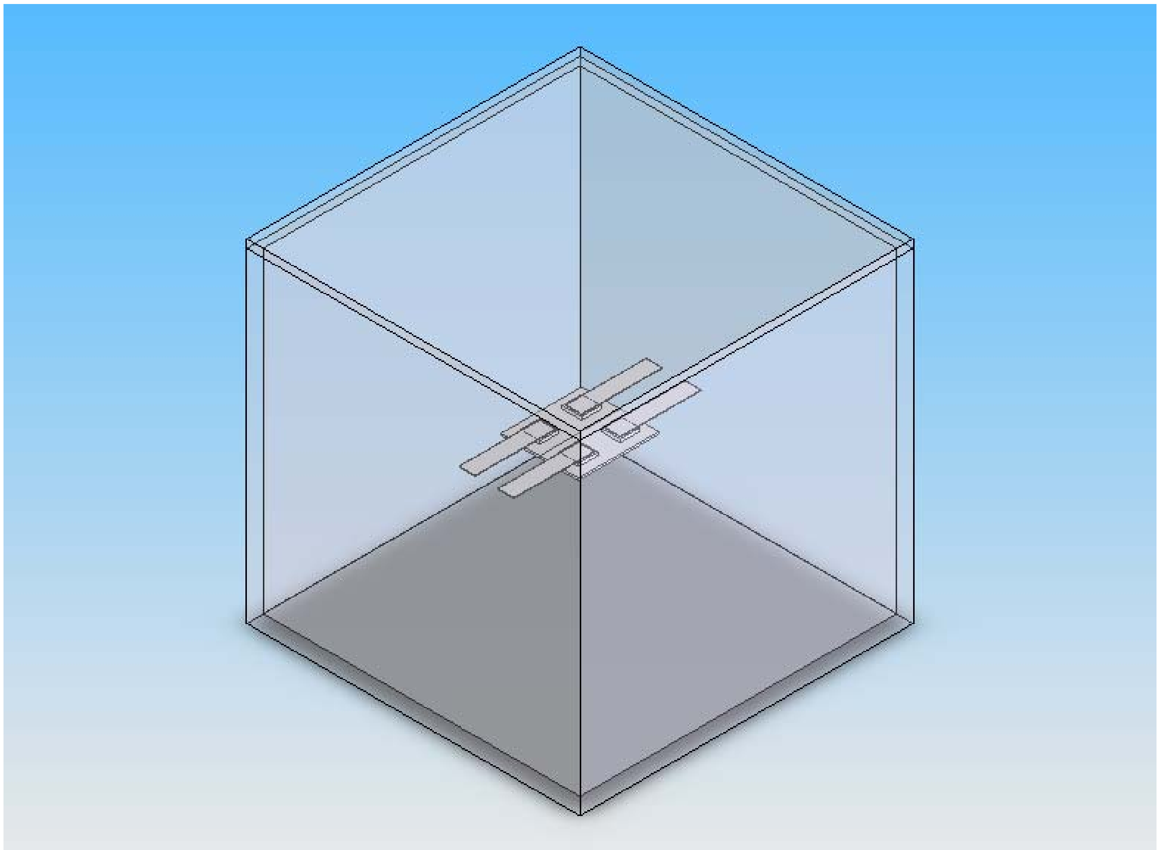

Figure 3. A diode assembly shown in its thermal simulation setting. The aluminum box containing the diodes has been made transparent in this view.

Figure 4 is a diagram of the heating power applied to the diodes collectively in all of the pulsed thermal simulations. Each pulse is 0.8 s wide, with a maximum total heating power of 80 W. In a 4-diode device, each diode is heated with 20 W per pulse. In a 2-diode device, each diode is heated with 40 W per pulse. This function was programmed into the simulation as the heat source.

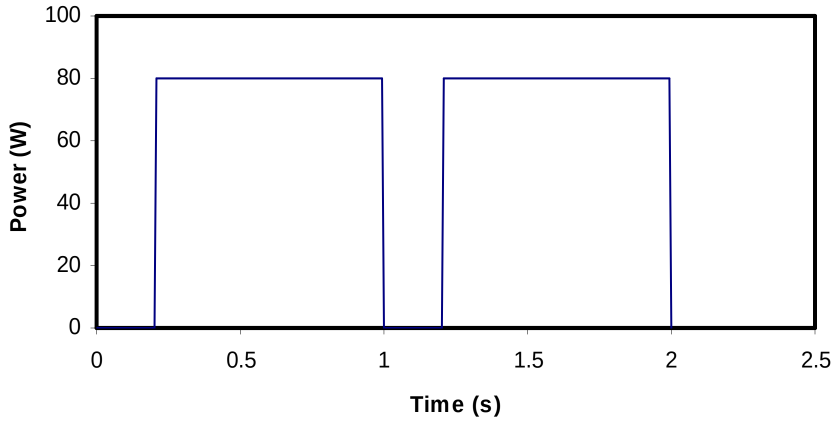

Figure 4. Pulsed heating of the SiC diodes as a function of time. Peak power is total combined power in all diodes.

I defined the initial temperature of the entire simulation body—diodes, aluminum box, and oil—to be 80 °C, an ambient temperature common in automotive environments. The temperature of the outside surface of the box is specified to be a constant 80 °C, serving as a heat sink for the simulation. Maximum temperatures on the SiC diodes were recorded at the end of each pulse, at 1 second and 2 seconds, respectively.

3. Pulsed Power Simulation Results

When I simulated pulsed heating of the 4-diode setup, I recorded a maximum temperature on the diode assembly of 110 °C at t = 1s, the end of the first pulse, and 119.4 °C at t = 2s, the end of the second pulse. Figure 5 is a contour plot of surface temperatures on the diode assembly at t = 2s. We see a maximum temperature increase of approximately 40 °C during pulsed heating.

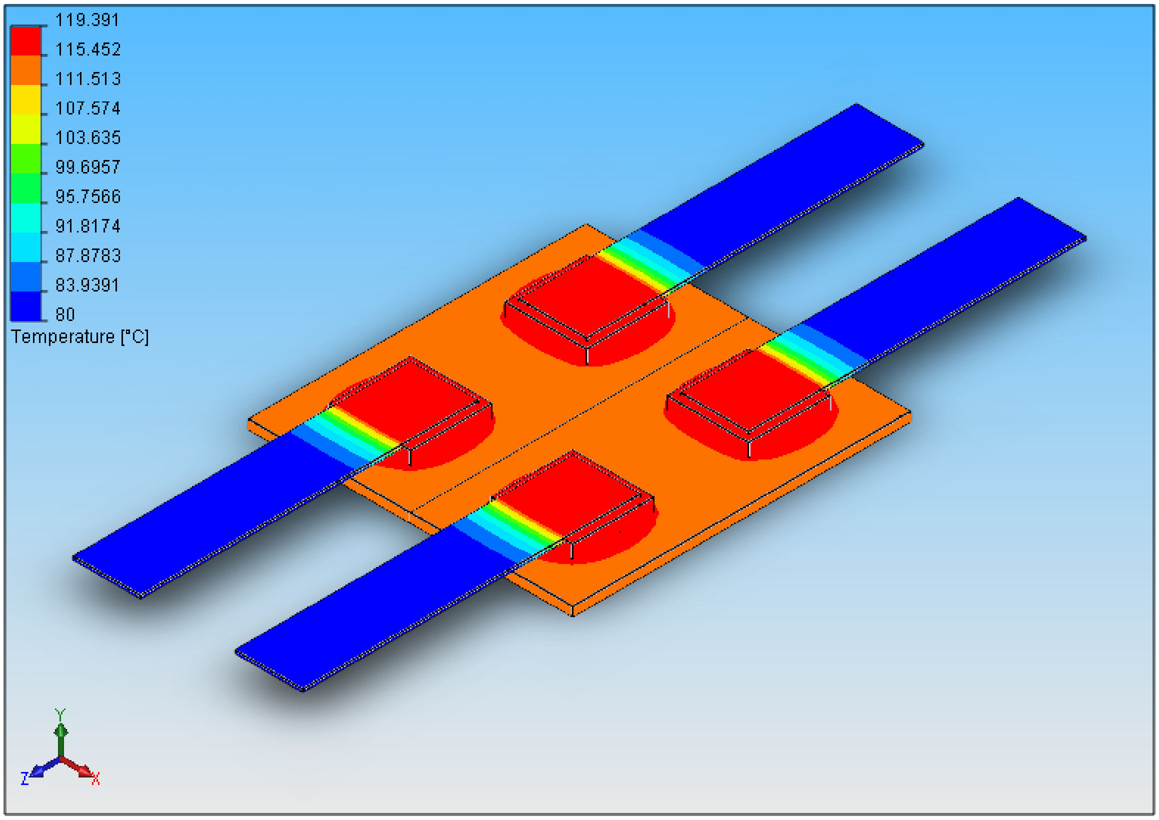

Figure 5. Contour plot of surface temperatures of the 4-diode assembly at t = 2 s.

When I simulated pulsed heating of the 2-diode assembly, I recorded a maximum temperature on the diode assembly of 120 °C at t = 1s, the end of the first pulse, and 142 °C at t = 2s, the end of the second pulse. Figure 6 is a contour plot of surface temperatures on the diode assembly at t = 2s. Thus, maximum temperature increase during heating was calculated to be 62 °C. The temperature increase here is greater than that for the 4-diode assembly, but it did not scale linearly with power—doubling the power per device did not lead to a doubling of maximum temperature. The temperature also remained in a range which should be safe for operation; temperatures much above 200 °C could threaten component integrity.

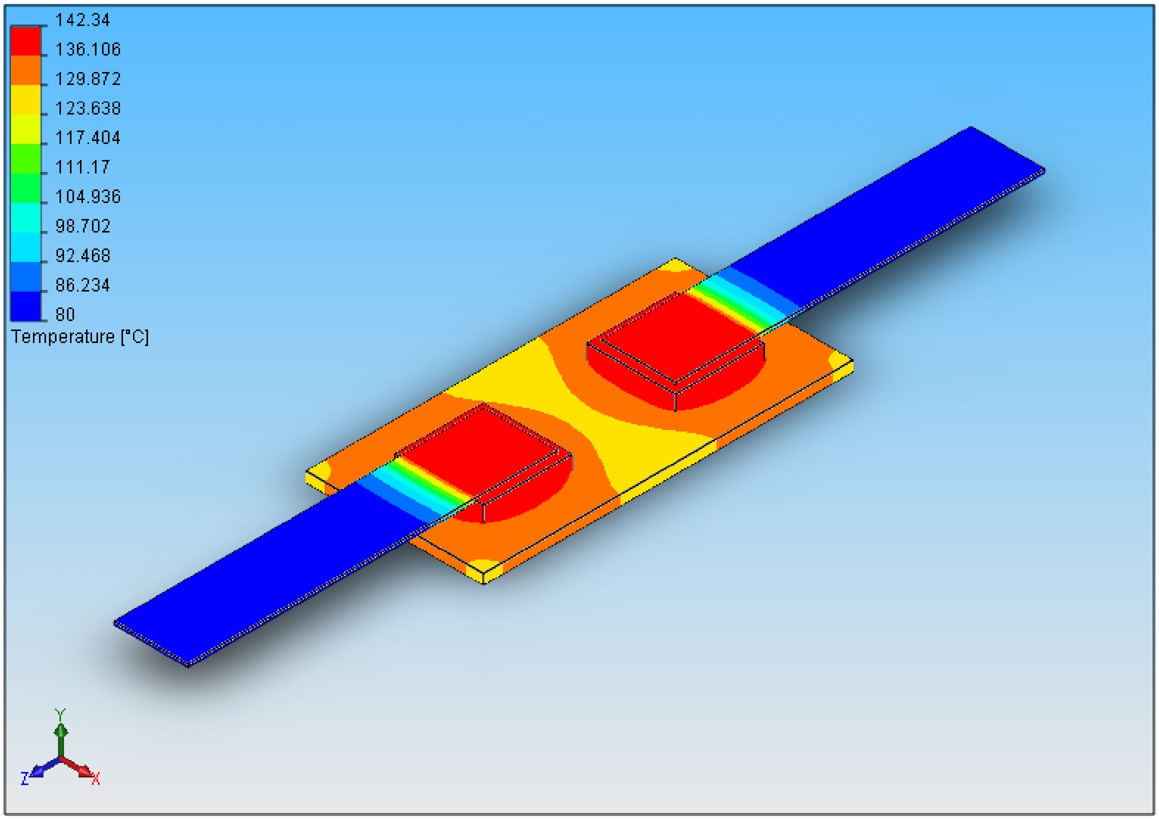

Figure 6. Contour plot of surface temperatures of the 2-diode assembly at t = 2 s.

Figure 7 is a cut plot of temperature contours in and around the diode assembly at the end of the second pulse, the point of maximum temperature rise. The contour plot is projected on a plane cutting through the diode assembly. It shows the limited extent of temperature increase in the oil around the SiC devices during heating. Although I chose to use a volume of 1 quart of oil for this simulation, it appears that our results will not change significantly with changes in oil volume because so little of the oil is being heated by the diodes.

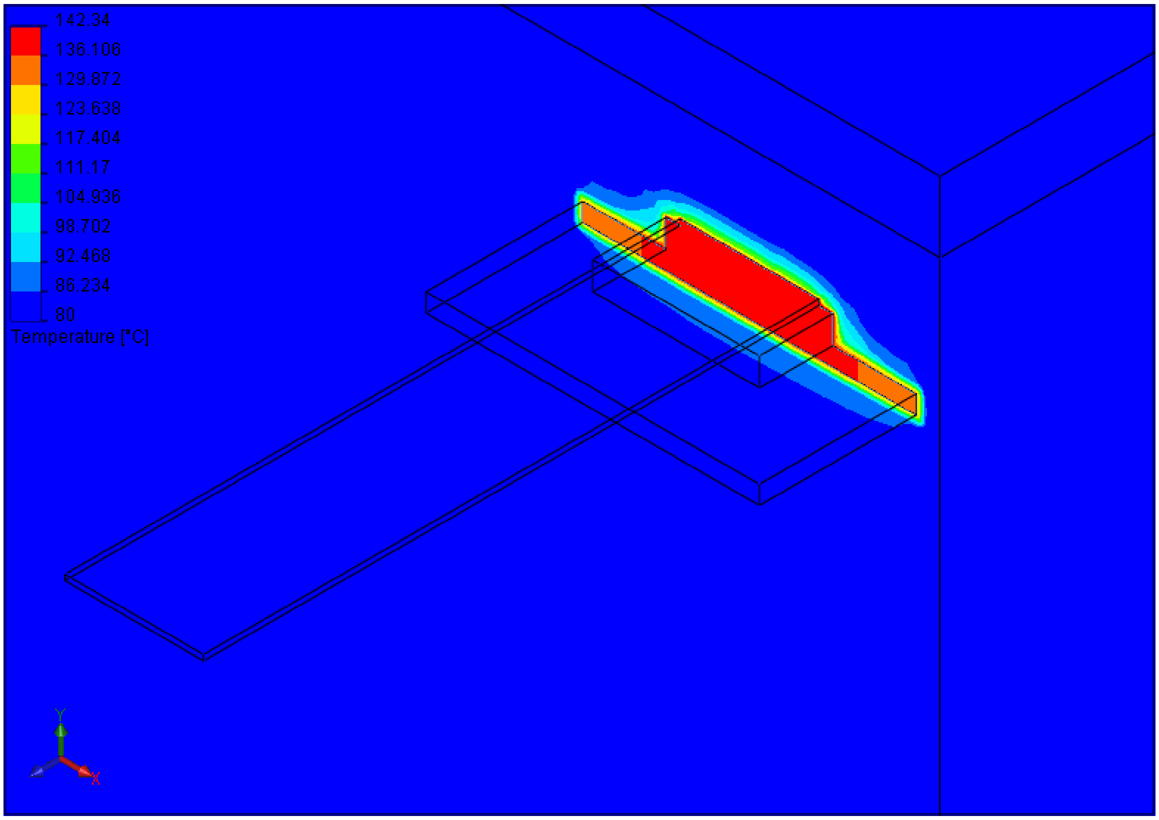

Figure 7. Cut plot showing the temperature distribution in the device and surrounding oil at t = 2 s.

Figure 8 is a plot showing the direction of convective flow of the oil around the diode assembly calculated by FloWorks during the heating simulation. This plot should be taken as a qualitative plot, rather than a quantitative measure of fluid velocity or mass flow.

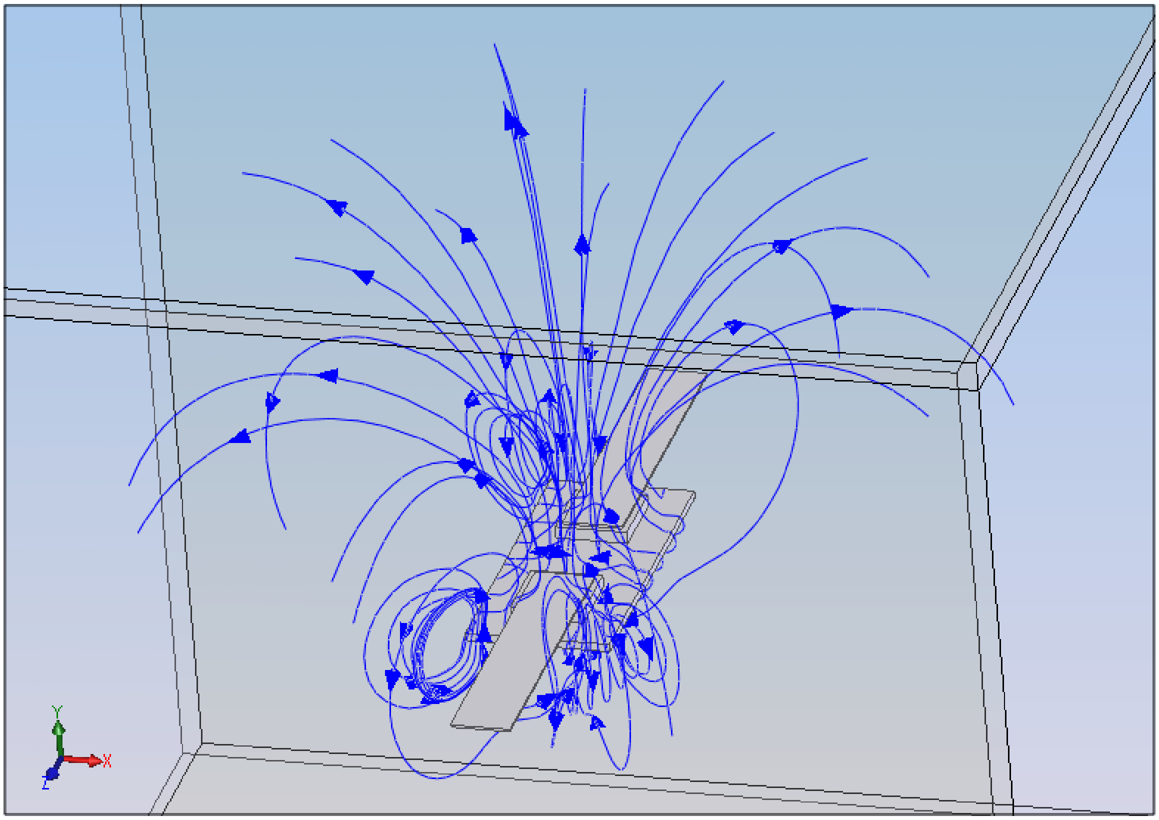

Figure 8. Trajectories of convective oil flow near the SiC devices during heating.

4. Simulated Heating with Periodic Functions

I attempted to simulate the heating of the diode assemblies with a periodic function, roughly mimicking the heating performed in laboratory evaluations with rectified wave signals. The function I devised to simulate heating power in the diodes was a sawtooth wave with a period of 16 ms and a frequency of 62.5 Hz. The peak power was a combined 80 W for all the diodes. A diagram of a portion of the signal is shown in Figure 9.

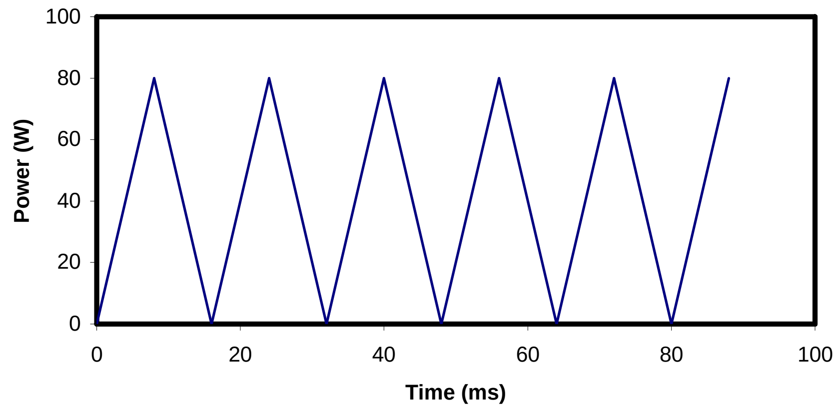

Figure 9. Sample of the periodic function used to simulate heating of diode assemblies.

The signal was applied for a total of 60 seconds in this simulation, which I assumed to be enough time to reach a steady state temperature in the model. The results of the simulation show the limits of FloWorks as a tool for predicting changes in temperature in a system as it is heated by a steady signal, rather than a pulsed signal. Figure 10 is a plot created during the FloWorks calculation which shows maximum temperature, in degrees Celsius, in the diodes over the 60 second simulation time.

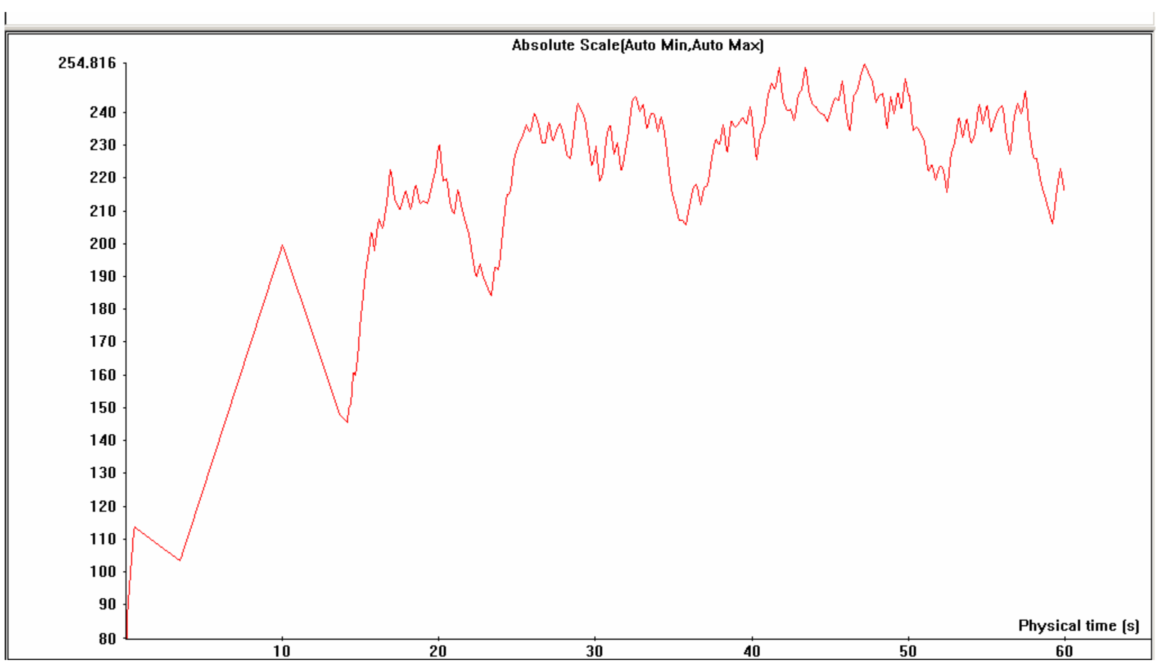

Figure 10. Maximum device temperature in degrees Celsius calculated for the 2-diode model during heating by a periodic function over 60 seconds.

The 60 seconds of simulated physical time was performed with 210 iterations. The problem with FloWorks appears to be that the simulation does not break up the period of simulation evenly. The first 10 seconds of the simulation was performed in only 10 iterations; the remaining 50 seconds was done in 200 iterations. Thus, the first few seconds of temperature calculations show a series of jagged peaks rather than a smooth increase in temperature. Even after the first few seconds, the simulation does not rise smoothly to a temperature plateau; instead, maximum temperature swings wildly within a range of more than 40 °C. This result is not physical.

The last 30 seconds of the simulation show a mean temperature of approximately 230 °C. Compare that result to a steady state simulation I performed, in which the diodes were heated with a constant 40 W total power. This is the power, averaged over time, put into the diodes by the sawtooth wave in the time dependent simulation. This steady state simulation, with all other factors the same as the time dependent simulation, calculated a maximum temperature of 240 °C. The steady state calculation of heating power into the diodes compares well with calculation of heating by a periodic signal over an extended time, and requires much less time to perform.

5. Conclusions

I performed thermal simulations of SiC diodes heated by twin pulses 800 ms wide with total peak heating losses of 80 W. When submerged in one quart of BP oil, heat was transferred by convection away from the heated diodes. Under these conditions, the simulation showed moderate temperature increases. A module with 2 diodes rose in temperature approximately 60 °C and a module with 4 diodes rose in temperature only 40 °C. With a starting temperature of 80 °C, both of these results keep the peak temperature below 150 °C and well within safety margins.

Thermal simulations using long periodic functions as heat sources, mimicking steady state AC signals, do not show reliable convergence to an equilibrium temperature value. The temperature instead rises and falls randomly within a wide range over the simulation period. A steady state simulation using the average power of the AC signal as a constant heat input may yield as much useful information as a time dependent simulation using the actual AC signal.

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